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This report covers the work performed in the development of two high specific power He-Ne lasers designed to operate in conjunction with optical tracking systems at 6328 Å only, with an objective of 50 mw single mode power output in a length of 50 cm maximum. The report discusses the areas of major study and indicates the areas of major accomplishments. Also discussed in detail are the areas requiring further refinements. Recommendations and conclusions based on the experience and results obtained are also listed.

Author

1.0 INTRODUCTION

The program carried out at h nu systems, inc. under NASA Contract No. NAS 8-11613, has been concerned with the development of two lasers capable of providing 50 mw of 6328 Å radiation in a package not to exceed 50 cm in length. It was expected that to meet the goals of high power output in a very short length, advances in the present state of the art in several areas would be necessary. Many of the developments that directly relate to this program have been sponsored by h nu systems utilizing company funds, manpower and equipment. The company's serious intent to utilize, to the fullest extent possible, the opportunity provided by NASA support to permit realization of sophisticated and advanced high specific power CW helium-neon lasers is evident.

The areas which were considered the most critical and were attacked at the onset of the program were 1] techniques for reducing the losses in the optical cavity due to scattering and absorption, and 2] determining the optimum excitation techniques for a goal of maximum output power. To achieve the condition of a very high Q laser cavity which is absolutely essential for the achievement of high power, sources for optical surfaces who would be able to provide an increase in quality over the optics which were previously available were sought. Stringent, but necessary, requirements were placed on the quality of the optics in all areas affecting the cavity Q. Sources were also sought who could supply dielectric mirror coatings of sufficiently low scattering and absorption.

The initial stages of the research program were concerned with techniques of raising the cavity Q while trying to increase the transparency of the output mirror. This was followed by studies on the excitation mechanisms of the He-Ne type laser. These studies included tests on direct current (d-c) pumping, radio frequency (r-f) pumping and combinations of d-c and r-f excitation and effects of transverse and longitudinal magnetic fields on the pumping efficiency. Concurrently with the above tests, a mechanical design was generated which would provide as long a plasma tube as possible within the dimensional limits of the contract, without sacrificing mechanical stability or ease of operation.

Other areas of study, which are reported in detail in the following sections, include selection techniques for obtaining low scatter optical surfaces such as mirror substrates and Brewster windows, determination of optimum mirror transparency for the final laser cavity, selection of Brewster windows based on flatness and parallelism requirements, and tube fabrication and processing techniques for the attainment of high power and long life.

2.0 MECHANICAL DESIGN CONSIDERATIONS

The basic external mechanical design of the laser is shown in enclosure 1.

To attain the maximum active plasma length in a gas laser whose overall length is 50 cm, it is necessary that the laser incorporate several radical departures from conventional units. The steps that have been taken to achieve this are:

a) The mirror adjusting apparatus has been removed from the ends of the conventional optical cavity to eliminate all of the space normally occupied outside the cavity by micrometers and their associated mechanism.

b) The axial length of the mirror adjusting mechanism has been compressed, without sacrifice in accuracy, through development of a mirror support structure that provides stability, reproducibility, accuracy, dynamic range and resolution consistent with the performance objectives of the laser, while conserving axial length and thereby reserving the maximum active length for the plasma tube.

c) Angular and linear adjustment mechanisms have been provided for the laser mirrors that are consistent with requirements for optical tracking systems and that will permit mechanical tuning of the optical frequency of the laser when it is operated at a power level consistent with a single axial mode (single frequency).

As will be discussed below, the rigid adherence to the boundary condition of conservation of axial length in the optical cavity has resulted in a design in which the actual available space between mirror surfaces in the optical cavity is as much as 462 out of 500 mm, or well over 92%, of the available cavity space.

Almost all of the remaining length of the laser is required for the thick 50 mm diameter interferometer mirrors of the laser cavity.

2.1 Orthoaxial Micrometers

In conventional gas lasers cavity mirrors are adjusted by coarse micrometers that are located on the end plates of the laser container. The provision of a conventional mirror adjusting mechanism with 2-inch micrometer drives in the 50 cm laser cavity would prohibitively waste space available for an active plasma tube. After two design evaluations, an orthogonal drive mechanism, based upon a new mirror adjustment principle, was developed for use in the 50 cm lasers. This design utilizes large micrometers placed on the sides of the optical cavity. The design not only saves valuable space for the plasma tube but increases the ease with which alignment adjustments can be made, as all of the micrometers are easily and directly viewed from above the cavity. To conserve lateral space and enhance instrument readability, the angle adjusting mirrors which are located at the output end were tilted at an angle that is both convenient and aesthetically pleasing.

The axial mirror adjusting mechanism presented a special problem in that incorporation of the precision linear drive mechanism with the 2-inch diameter mm micrometers required more space than available in the cube size. Furthermore, the micrometer scale could not be read with ease. A novel design was developed that places the operating and indicating mechanism at the optimum physical location for the linear drive mechanism. An optical transfer system is used for scale reading. This includes a set of two orthogonal prisms developed to gather room light for the micrometer scale illumination. The same prisms transform the micrometer scale reading to a convenient location for observation.

The designs incorporating the orthoaxial micrometers provides an effective increase of more than 25 percent in the active length of the plasma. This represents a very significant gain in the power producing capability of any gas laser of short length.

2.2 Taut-Band Orthogonal Mirror Drives

The angular position of the mirrors in a conventional CW gas laser is derived by twisting torsional members about the two orthogonal axes of a mirror adjusting mechanism. The latter is driven by paraxial micrometers. The premium value of active plasma tube length in the 50 cm laser and the right-angle drive properties of the orthoaxial micrometers, when considered in view of the need for precision angular adjustment of the mirrors in lasers designed for use in optical tracking, led to the evaluation of two designs for orthogonal mirror adjustment. The stressed tube design, which was first conceived, was abandoned in favor of the flat plate taut-band design as the latter was more conservative of axial cavity length.

The taut-band design utilizes an Invar (to minimize thermal drift) inclined plane sleeve on the mm micrometer to drive a sapphire (to minimize stiction) cylinder bearing that is mounted on the tip of a motion transfer spring. The latter applies a torque that twists a precision web plate. This consists of a nest of concentric circular rings interconnected by two orthogonal webs to form the axes about which mirror motion takes place. The motion transfer springs have a spring constant that differs from the web plate so that the desired reduction in translation can be obtained without the use of bearings (which might otherwise introduce backlash, loss of calibration and hysteresis).

This mechanism is able to achieve reproducible angular mirror adjustments of the order of 0.02 arc sec. It is, of course, necessary that the precision angular adjustment be supplemented with a gross angular adjustment so that the optical cavity may be brought to the initial alignment necessary to establish laser action. Provision is made for the latter adjustment by set screws located in the end plates of the laser cavity.

It is believed that the new design of the angle adjusting mechanism development for this cavity is of a precision consistent with achieving maximum performance from the laser through both provision of superior angular resolution and conservation of axial cavity length. It is anticipated that this precision may also prove invaluable in the precision boresight steering of the laser beam.

2.3 Axial Parallelogram Mirror Drive

The frequency of a gas laser is determined, within the Doppler linewidth, by the optical path length between the mirror surfaces of the Connes interferometer cavity. The Doppler linewidth of a helium-neon laser, operating on the 6328 Å transition, is approximately 1500 mc/s. It can be shown that a laser designed to operate only on a single axial mode must be as short as 10 cm in length. A laser mirror separation of 46 cm as in the 50 cm laser, may support as many as three additional axial modes. If the output power level of this laser is reduced a level will be reached at which the laser gain is only sufficient to support a single axial mode (single frequency). For this condition it is desirable to be able to vary the physical length of the cavity so as to optimize single-frequency power output. It is necessary that a very precise mechanism be used if mechanical control of cavity length is to be achieved.

The precision linear adjustment mechanism developed utilizes a 2-inch (.002 mm minimum graduation) micrometer to drive an Invar inclined plane. The latter slides along a sapphire cylinder bearing that bends a right-angle motion transfer spring. The motion transfer spring provides a force through a set of vertical webs to displace a special parallelogram that supports the mirror. One end of the parallelogram is anchored solidly to the end plate of the laser cavity whereas the other terminates in the interferometer plate holder. The parallelogram is driven at the center of the upper member by the motion transfer spring through a central hole in the front vertical web. This design facilitates accurate axial displacement and also economizes on axial length.

The ultimate resolution of the axial displacement device will, of course, be limited by stiction. As in the case of the angle adjusting devices, these effects have been minimized by employing elastic structural deformation of assemblies in all cases except those required to couple to the micrometer drive, i.e. the conversion of rotation to displacement. In this case a cylindrical sapphire bearing minimizes stiction effects. The precision linear adjustment device is designed to provide a resolution of .0001 microns (or about 100 kilocycles in terms of optical frequencies). The precision mechanism is, of course, supplemented by a coarse mechanism consisting of set screws located in the end plate of the cavity that permit appropriate alignment of the interferometer mirrors for laser action.

The new design developed to permit linear position control of the interferometer mirror provides a saving in active plasma tube length, as well as providing the most precise adjustment of the optical cavity. This enhances the possibility of obtaining both maximum power output under single and multiple axial mode conditions and also provides mechanical control of the output frequency of the laser for laboratory heterodyne experiments.

2.4 Recessed Interferometer Plates

An important additional saving of active cavity length was effected by designing the interferometer plate holders so that the plates were actually suspended inside the 1/2-inch stainless steel laser cavity end plates. This design tends to offset, somewhat, the requirement for thick interferometer plates, a requirement that is necessitated by the stringent specifications that must be placed upon the optical quality of these cavity elements.

2.5 Tube Support Structures

The laser tube is supported in the laser package at three points along its length. Each of the supporting members emanates from the basic invar supporting tube to which the stainless steel end plates are welded. The materials chosen for the support structures are such that, thermally, the relative optical axis of the laser system will be the same through a very wide range of ambient temperatures. This technique of supporting the mirrors and laser tube from the same reference plane will allow high stability over long term periods of operation.

3.0 PLASMA EXCITATION MECHANISMS

The main reactions in the He-Ne gas phase laser system are described and referenced in the comprehensive treatment by Bennett, (Ref. 1). An approximate energy level diagram is shown for the He-Ne system in Figure 1 in which the major transitions are designated. For this particular application, transition B, which results in the 6328 Å radiation, is of prime interest and is to be optimized for maximum power output from a laser cavity. As can be seen from the diagram, the competing processes, transitions A and C, can inhibit the desired transition by the process of depleting the upper laser level [Transition A] and by loading up the lower laser level [Transition C]. Since the probability of Transition A occurring is proportional to the difference in the population densities of the two laser levels, it is necessary to discourage the competing processes.

Generally, the competition between the several lines only becomes noticeable when the He-Ne gas is emitting radiation by stimulated emission, as in the case of a tuned laser. For this case, the gain of the 3.39 micron line is very large compared to the gain of the 6328 Å line, especially in small-bore, high-gain lasers, so that very large losses selective to the 3.39 micron line are absolutely necessary to obtain lasing action at 6328 Å.

In most instances, the narrow band reflecting optics used in the laser cavity are sufficiently lossy, at 3.39 microns that the 6328 Å line is able to oscillate quite well, but for maximum power output, the 3.39 micron line must be further inhibited by other techniques which are described below.

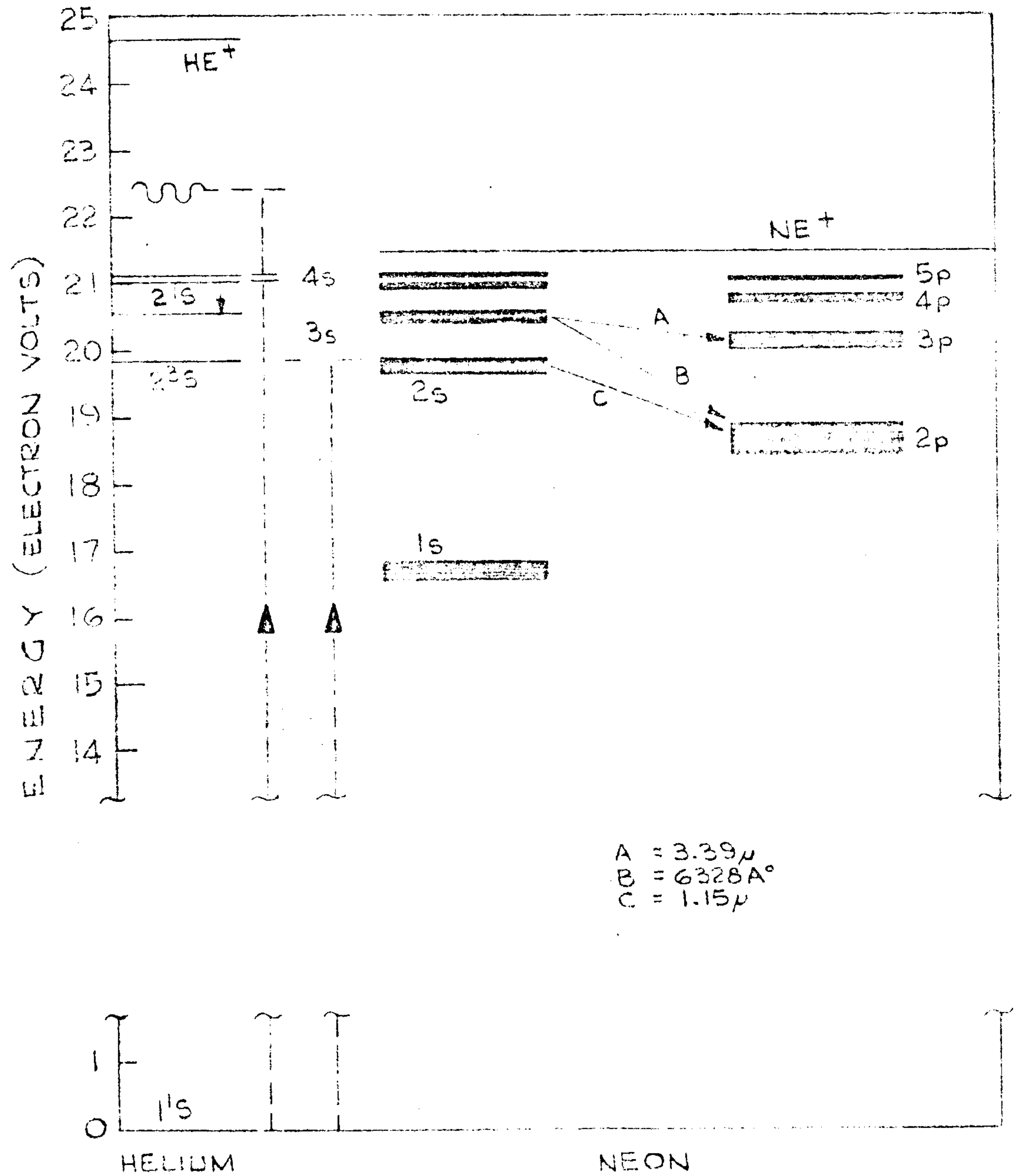


FIG 1
HELIUM-NEON ENERGY LEVEL DIAGRAM
SHOWING TRANSITIONS OF INTEREST

Also listed in the following sections are several techniques used to increase the possibility of higher power output from the basic gas excitation viewpoint.

3.1 Isotope Effects

To further enhance the gain and thus the possible maximum power output, the use of He^3 in the He-Ne gas mixture, instead of the natural He^4 isotope has been found (Ref. 2) to increase the inversion ratio between the lower and upper laser levels. Approximately 25% improvement can be obtained in the single pass gain at 6328 Å if this isotropically pure He^3 gas is used. He^3 of a low tritium content was procured by h nu systems as licensed through the AEC, and used during the course of the contract. It was found that for the operating conditions of the laser tubes generated during this program, a consistent increase of about 20% in total power output was observed with the use of He^3 over natural helium.

As a further refinement, the utilization of the pure Ne^{20} isotope offers a more symmetrical Doppler broadened gain versus frequency curve for the 6328 Å line. By using these two isotopically pure gases in the laser tubes constructed during this program, the laser spectral response has been enhanced as well as improving the gain.

3.2 Magnetic Field Effects

The dominance of the 3.39 micron infrared transition can be somewhat reduced by the addition of a magnetic field in the vicinity of the laser bore. Ahmed, et al, (Ref. 3) have studied this magnetic effect and have found a geometrically preferred direction for the maximum effect. The effect of the magnet field is to broaden the natural line shape of the infrared transition thereby reducing the gain of this transition.

Several tests were performed with bar magnets to determine the extent of the magnet field effect, and to determine the relative effects between transverse and longitudinal fields. It was found that for larger bore tubes of about 5 mm inside diameter, the increase in power output was as large as 22% with the addition of about 300 gauss at the tube bore. As the field was increased above 300 gauss, the power output was again reduced. The above results were obtained for a transverse magnetic field. However, it was possible to obtain the same results with a longitudinal field.

When the same tests were applied to smaller bore tubes, the percentage increase in power output dropped off as the tube bore was reduced. Essentially no effect was seen for a tube bore of 2 mm diameter or smaller. This decreasing effect with smaller tube diameters may be understood on the basis of diffraction-loss limited gain at 3.39 microns with small bore tubes.

3.3 Variable Diameter Effects

For the He-Ne gas laser system, two areas in which a varying tube diameter has a large effect is 1] power gain of the tube, and 2] power loss due to diffraction. Gordon and White (Ref. 4) have determined experimentally similarity laws for the effects of tube pressure and diameter on the gain of a He-Ne laser. From their work, it has been determined that the maximum gain value varies closely as D^{-1} where D is the discharge tube diameter, and that for maximum gain conditions the gas pressure tube diameter product is a constant for varying diameters. Therefore, by going to smaller diameters and higher pressures, greater gains can be realized.

However, at small diameters, diffraction losses become large, tending to off-set the increase in gain. Li (Ref. 5) has evaluated the integral equations for the diffraction losses, phase shifts and field distribution functions of a laser with circular mirrors. The curves generated by Li show dramatically the rapid rise in diffraction loss when the bore diameter is reduced beyond a point where the Fresnel number, N, falls to approximately unity. The Fresnel number of a system is given by

$$N = a^2/\ell\lambda$$

where a = tube bore radius

ℓ = tube length, approx.

λ = wavelength of interest

For the 3.39 micron line in a tube of about 50 cm in length, the Fresnel number, N, for a 2 mm bore tube would be $N = 0.6$.

At this value of the Fresnel number, the diffraction losses for the 3.39 micron line would be quite large compared to the gain, resulting in a much reduced power. As the diffraction loss curves have such a large negative slope as a function of N, doubling the diameter [N —> 2.4] would reduce the diffraction losses by a factor of over 500 favoring a much stronger oscillation of the line.

For the magnetic field experiment, the extra losses on the 3.39 micron line introduced by the presence of a magnetic field will, therefore, have a smaller and smaller effect as the tube diameter is decreased.

Because of the difference in wavelength between the 3.39 micron line and the visible 6328 Å transition, the diffraction loss will be quite different for each one. For a particular geometry, the Fresnel numbers for these two lines differ by a factor of 5. By choosing the proper tube diameter, length and mirror configuration, a large diffraction loss can be obtained for the infrared line while the visible line still has a relatively low diffraction loss.

To take advantage of the gain-diffraction loss trade-off with bore diameter, it would be somewhat advantageous to shape the inside bore of the tube to conform to the shape of the optical beam within the bore. This would allow smaller diameters to exist over portions of the tube without significantly increasing the diffraction losses. For the case of a hemispherical cavity, which was used for most of these tests, the intercavity beam shape is a cone with the apex on one mirror and a large spot on the other mirror limited in size by the tube bore aperture.

An experimental laser tube was constructed where the bore conformed to the cone shape of the laser beam to take advantage of the higher gain in the region of the smaller diameters. The technique did not prove successful in obtaining higher powers than with a conventional cylindrical bore. As was determined in other studies with d-c pumped tubes, the power output of a laser depends sharply on the current density in the laser bore. For the cone shaped tube, the current density variation along the bore was found too large to maintain a near optimum condition. As time did not permit further investigations of this approach, other techniques such as d-c plus r-f excitation which may get around the problem of a large variation in current density, were not pursued.

Diffraction losses play another important role in the design of a laser tube for which single mode operation is required, as is the case for this contract. For a sufficiently low loss system, more than one longitudinal mode will oscillate in the laser cavity resulting in an output beam composed of several distinct spots, each of which have a different phase value. To discourage the higher order modes from propagating, selective losses to these modes must be imposed in the cavity. The only type of loss truly selective to higher order modes are diffraction losses which are determined primarily by the geometry of the laser tube and mirror system. Therefore, a laser must be designed such that all the losses within the cavity, including diffraction losses, are just large enough to keep all but the lowest order mode from oscillating. Unfortunately, this cannot be done without imparting some unwanted losses on the lowest order mode resulting in a limit for maximum power output for single mode operation substantially below that for multimode operation.

3.4 Effect of R-F and D-C Pumping

To determine the requirements for the power supply to be used with the final unit and to establish the best pumping technique for obtaining the desired objective of maximum laser output power, several excitation tests were run on tubes with various bore diameters. The excitation tests were run for d-c pumping, r-f pumping and a combination of d-c and r-f with the laser fill pressure being held as a controlled variable.

In the case of d-c pumping alone, the similarity laws for the tube pressure and diameter for He^3 and Ne^{20} were measured and found to be

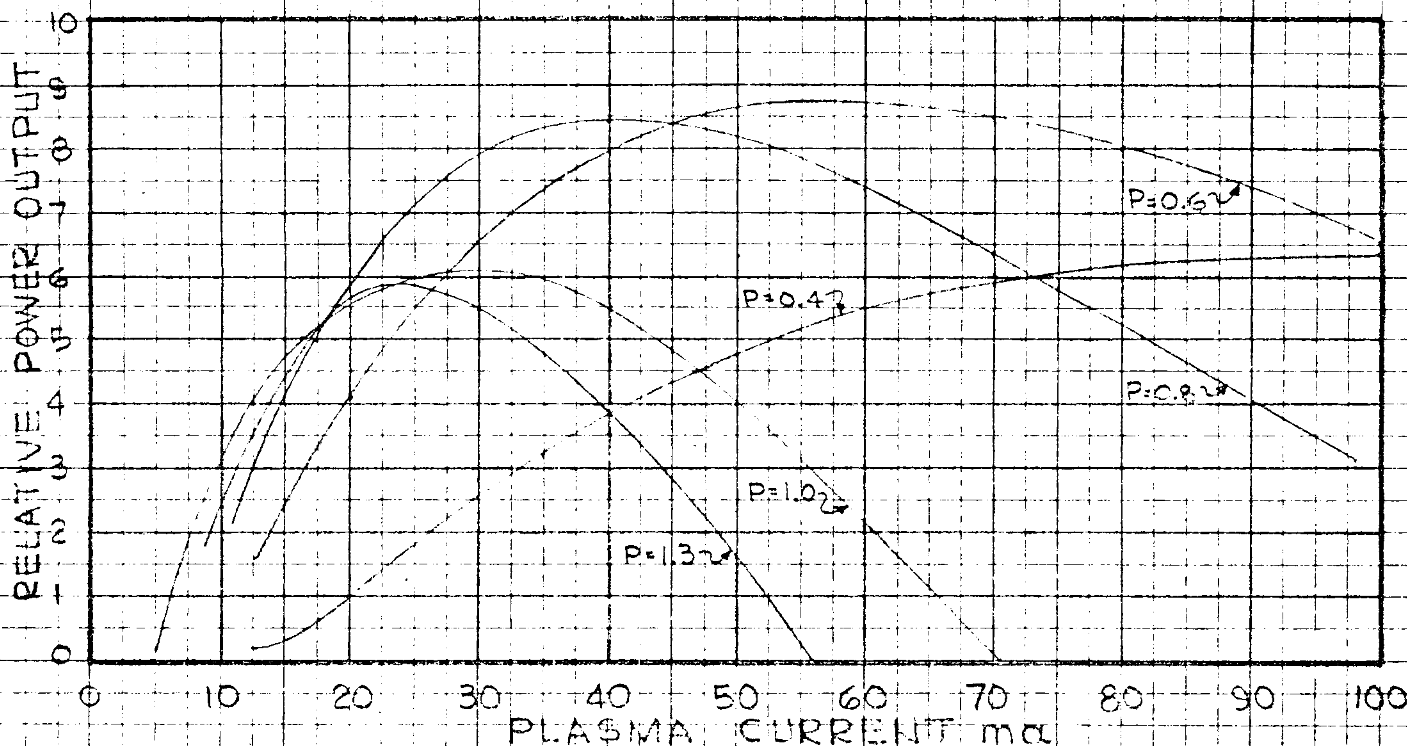
$$PD \approx 4.0 \text{ Torr-mm}$$

for a 7 to 1 mixture of He to Ne. Pressure data were determined by a capacitive manometer accurate to better than 1%. The tube current for maximum power output as a function of tube diameter followed a relationship of

$$\frac{I}{D^2} = 2.5 \text{ ma/mm}^2$$

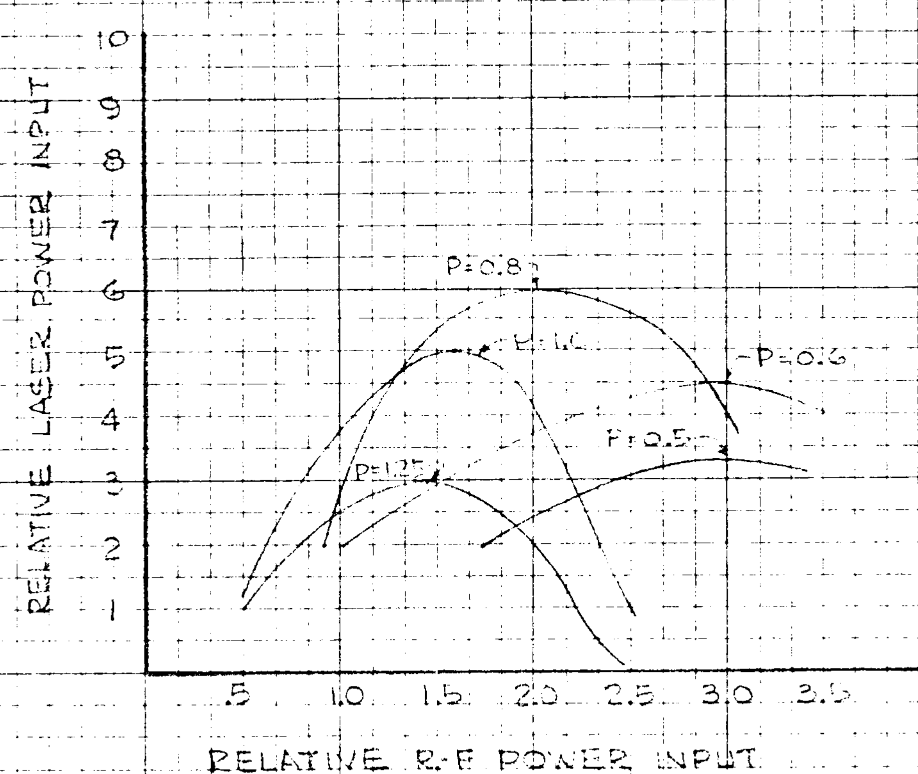
for tube diameters over the range of 2 to 5 mm.

The relative power output as a function of tube current and pressure was also measured for several bore sizes. Figure 2 is a graph showing the results of these measurements for one tube.



OUTPUT OF LASER AS A FUNCTION OF D.C. EXCITATION CURRENT FOR VARIOUS RELATIVE PRESSURES

FIG. 2



OUTPUT AS A FUNCTION OF R.F. EXCITATION FOR VARIOUS RELATIVE PRESSURE.

FIG. 3

Other bore sizes followed the same pattern. An optimum pressure and current is apparent from the graph for maximum power output. Also, for lower pressures, the maximum power output region is much less sensitive to variations in plasma current.

The above measurements were repeated for the case where only r-f pumping was utilized. As can be seen in Fig. 3, the results were quite similar to the case where d-c pumping alone was used except that the maximum output for r-f pumping was lower than for d-c pumping, and occurred at a slightly higher pressure. In both cases the same tube and same gas mixture was used. It is obvious that continued increase in input power to the laser does not result in greater power output once saturation has been obtained.

Experimental work originating at the California Institute of Technology, under the guidance of Nick George [Ref. 6] has indicated that improvements in optical gain can be achieved through simultaneous r-f and d-c excitation of the laser. The improvement is hypothesized to be associated with a change in electron energy distribution in the plasma favoring the laser transitions. More exhaustive tests at h nu systems on multiple pumping have indicated that any increase in power output with this technique would be only a few percent, if at all, and that it would occur at a pressure higher than that for optimum d-c excitation. It was apparent that the disadvantages associated with r-f pumping (shielding against R.F.I., more complex power supply, etc.) were greater than the possible advantages, so that the combined excitation technique was not considered applicable to this program.

4.0 BREWSTER WINDOWS AND MIRROR SUBSTRATES

It can be shown that as the active length of a laser is reduced the magnitude of the effect of any slight imperfection in an optical component that interacts with the cavity radiation is greatly magnified. A cavity $1/m$ times as long as another cavity will not, in general, deliver $1/m$ times the power output. There will be m times as many reflections from the cavity mirrors and m times as many traversals through Brewster windows of the plasma tubes. It is, therefore, absolutely essential that the lowest attenuation, highest uniformity quartz be used for the end windows of the plasma tube. It is further necessary that the quality of the surface finish of the windows and mirror substrates be such that scattering losses are minimized. The finest surfaces must, of course, be processed with extreme care to ensure that they do not become contaminated by dust in subsequent processing, particularly that surface which is interior to the plasma tube. It has been found that the best plasma tube performance can be attained if the windows are attached to the plasma tube as one of the final operations in assembly and processing of the plasma tube. The best performance that has been obtained to date has resulted from the use of 1/8-inch thick Schlieren-grade quartz windows that are homogeneous to better than 1/20 fringe within the window, and are polished to yield a scattering loss of 0.05 percent or less.

Unfortunately, not all windows obtained from the same source at the same time will have identical characteristics. It is essential for high power applications that the best substrates and windows be carefully selected from a group for use in the final laser cavity. The selection process can be broken down into two distinct areas, 1] acceptance based upon surface figure and wedge between surfaces, and 2] acceptance based upon surface finish. Instrumentation has long been established for the measurement of surface figure, especially for the measurement of surface flatness. Interferometer type test equipment is available for measuring surface flatness and wedge angle between surfaces to an accuracy to better than 1/40 wave. All windows and substrate surfaces were interferometrically checked before acceptance for final use.

The other area which critically effects the performance of the laser is the level of scattering from the surfaces of the windows and substrates. Generally, the absorption through the windows is very small, if the windows are made from quartz, and since the windows are placed at Brewster's angle with respect to the laser beam, the reflectivity for one polarization is essentially zero. If the windows are flat and the two surfaces are parallel, the only other source of loss to the laser beam is scattering from the window surface. Therefore, selection based upon low scatter is essential to the fabrication of a good laser tube.

For less critical applications than in this contract, surface quality can be examined with the aid of a high power microscope used in conjunction with a high brightness light source. Small scratches, sleeks, and poor polishing techniques can be observed this way. But for more critical applications more refined techniques need to be developed for choosing the lowest scatter surfaces.

The only technique readily available at the time of this contract for measuring the relative scattering characteristics was to actually use the surface in a laser cavity and note the resulting laser power under controlled conditions. Although this technique could be considered satisfactory for windows, it was a time consuming operation and required close attention to the laser operating conditions so that results between tests could be accurately compared. The main disadvantage to this technique was that mirror substrates could not be checked without first applying a multilayer dielectric mirror coating to the substrate surface. The variability of the coating was then necessarily included in the tests making evaluation of the substrate quality extremely difficult.

During the course of the program it became evident that a surface quality comparator capable of measuring low levels of scatter was needed in order to properly discriminate between good and excellent optical surfaces.

The requirements of the comparator would be 1] the device should be capable of measuring absolute scattering figures for both coated and uncoated surfaces, 2] the device should have a sensitivity high enough that the best obtainable surfaces would still give readings above the noise level of the instrument, and 3] the device should be simple to operate so that surface scattering figures could be made in a reasonably short time.

A comparator was designed during the contract to satisfy the three items above. It utilized a small but bright He-Ne laser as a light source and a sensitive photomultiplier tube as a detector. A mechanical breadboard of the comparator was constructed and the device was tested for its capability of distinquishing between low scatter surfaces. The device proved to be quite sensitive and with the proper adjustments could also be used for the selection of best quality dielectric mirrors. Because of the timeliness of the design and construction of the comparator, its usefulness came too late in the period of the contract. The final mirror substrates and windows had already been chosen by other techniques.

Early in the contract, the difficulty in obtaining mirror substrates of the quality necessary for this program was realized. At that time the only group which h nu systems felt had the capability and technique for supplying the mirror substrates was Halle of Germany, represented by Industrial Optics in the U.S. Stringent, but achievable, specifications were placed not only on the surface figure of the optics, but also on the surface smoothness. After the order had been placed with Industrial Optics several other organizations were sought as a back-up supplier to Halle. Throughout the entire course of the contract, various suppliers have been attempting to meet the specifications required with only limited success. The major problem area is surface quality. The polishing techniques required to reduce the r.m.s. surface roughness to an acceptable value for a laser mirror substrate are not well enough established to allow a reasonable yield of good surfaces. Perry* of the Bell Telephone Laser Coating Laboratories, has indicated that he has obtained substantial improvement in laser mirror surface quality when he has generated a substrate by cleaving a quartz crystal inside the vacuum system, and immediately coating the fleshly cleaved surface. This no-polishing technique essentially proves the

* Darwin Perry, BTL, Private Communication

desirability of obtaining better quality substrate surfaces for the attainment of maximum reduction of laser cavity losses.

5.0 MIRROR COATINGS

In Sec. 4.0, the importance of obtaining extremely high surface quality in the mirror substrates was stressed. There it was pointed out that significant gains in power output could be obtained using the same dielectric coating techniques when the surfaces were noticeably more free of scratches, cracks and surface micro-irregularities. Given a perfect substrate, it is absolutely essential that the multilayer dielectric films be applied in a manner that ensures minimum absorption and scattering losses.

For any dielectric surface the optical characteristics can be described by the simple relationship

$$r + t + a + s = 1$$

where r = reflectance

t = transmittance

a = absorptance

s = total scattering

For a laser mirror, which is made from alternate layers of thin dielectric material, the t, a and s quantities represent loss to the laser cavity.

For the case of a He-Ne 6328 Å laser where the gain is rather low, $1 - r$, must be quite small (on the order of 0.02) for the laser to oscillate. It is absolutely necessary, therefore, to make the absorption and scattering losses negligible compared to t for maximum cavity Q, for each decrease in $a + s$ allows an increase in t, resulting in increased power output.

For the type of coatings generally used for the He-Ne 6328 Å laser [ZnS and cryolite or $ThOF_2$ layers] the absorption figure depends primarily on the purity of the materials used. The scattering figure also depends strongly on the purity of the materials used, but depends even more strongly on the technique of fabrication of the mirror.

During early tests, in which films of 9 to 15 layers were tested, it was noticed that considerable scattering existed from the surface of the mirrors. Further experiments were conducted using substrates of reasonably good quality where the number of dielectric coatings was about doubled, along with a definite attempt to increase coating quality. Doubling the number of layers and increasing the reflectivity on the non-output mirror was found to improve the performance of the test gas laser.

It was noted that despite increases in laser power output, considerable scattering was still present as evidenced by the brightness of the laser spot on the front surface of the mirror. Also, there was still a significant amount of depolarized radiation scattered from the Brewsters-angle windows. The primary source for this radiation comes from the directional scattering off the mirrors.

These tests emphasized that considerable improvement is still required in control of the mirror fabrication processes. Most commercial organizations are not yet equipped to offer the ultra-clean, time consuming techniques necessary in the preparation of top quality mirrors. Also, evaluation of the newly deposited mirror surfaces is difficult as measures of performance need to be defined. Valid tests are lacking that will enable mirror coating quality to be assayed and adequately controlled.

That these factors exercise enormous effect upon the performance of CW gas lasers has been made evident by the striking increase in power output recently obtained at the Bell Telephone Laboratories through the improvement of the quality of dielectric films [Ref. 7]. The technical staff of h nu systems was aware of these developments early in the contract, through interchange of professional correspondence, even though the information has not become public knowledge. h nu systems made several attempts to determine whether or not this information could be released by the Bell Telephone Labs, so that the techniques might be adapted to the 50 cm lasers, thereby enhancing their performance characteristics. Management decisions at the Bell Telephone Laboratories dictated that the information not be made public until the NEREM Conference late in 1964. As soon as the information was made public h nu systems contacted Bell Telephone Laboratories technical personnel and arranged, with their authorization, a technical meeting at Bell Telephone Labs to inspect their equipment and facilities, and to discuss in considerable detail with the cognizant personnel the techniques used to improve dielectric surfaces so as to enable the increase of laser power output by nearly two orders of magnitude.

The company also took the responsibility for contacting the major optical coating firms known, through previous experience, to have produced films of unusually excellent optical quality.

It became apparent that none of the firms interviewed was either capable of producing the low scattering loss, low absorption films required, nor was any aware of the detailed techniques which would permit reduction of scattering and absorption losses.

As a result of our discussions with Dr. Eugene Gordon, Mr. Donald Perry, Mr. Stewart Miller, all of Bell Labs, and the counsel of such firms as Bausch and Lomb [Herron Optical Company,] Optical Coating Laboratories, Thin Film Industry, Optics Technology, and Perkin-Elmer, some progress has since been made in improving the characteristics of dielectric films supplied to <u>h nu systems</u>. At the conclusion of the contract, films received from Perkin-Elmer came the closest to that required. Two such mirrors were used in the final lasers.

For the purpose of evaluating the optics received during the course of the contract, a 2-meter long, 5 mm bore r-f excited laser was constructed which was capable of producing large enough cavity power that Brewster windows and other optics could be studied within the cavity and evaluated for quality. This laser was also used to determine the optimum mirror transparency to be used in subsequent experiments. A selection of mirrors on good quality substrates were obtained with transmittances ranging from 10^{-5} percent to 7 percent. With a standard mirror placed in the non-output end of the laser, the mirrors with different transmittances were cycled in the output end of the laser. It was found that a mirror transparency of about 2% provided the highest power output for this laser. It was also verified that the quality of the mirror coating was the largest single factor that affects the performance of the laser. A new, clean, good quality surface with 0.8% transparency resulted in a power output almost equal to the maximum obtained with a medium quality 2% mirror, even though a slightly poorer quality 0.8% mirror provided substantially lower power output.

Further tests of the same nature on smaller lasers indicated that the optimum transparency for the 50 cm long laser should be at least 1%, depending on the quality of the overall laser mirror. For mirrors with lower scattering and absorption the figure could be somewhat higher, allowing more power output.

The value of the optimum mirror transparency can be approximately calculated by the technique as outlined in Ref.1, where an estimate for the optimum transparency is listed as

$$T_{opt} \approx \sqrt{GL} - L$$

where G is the gain of the laser without mirrors and L is the scattering and absorption loss in the mirrors. For a laser of the configuration used in the 50 cm cavity [35 cm active plasma length and 3 mm I.D. bore], the maximum gain would be approximately 4% per pass for the lowest order mode if low loss (.05% per surface) Brewster windows were used.

Our experience with multilayer dielectric mirrors has indicated that the mirror loss can vary over a fairly wide range, even for new mirrors. Choosing a value for a "good" mirror of about 0.5%, the optimum value of the transmission can be calculated to be

$$T_{opt} \approx 0.9\%$$

Herriott and Schulte, [Ref.8] of Bell Labs have indicated the attainment of mirrors with scattering and absorption losses of less than 0.2%. For this value the optimum mirror transparency would be about 2.7%, allowing substantially more power output than the 1% mirrors used in the final lasers.

As can be seen, the proper mirror transparency varies rapidly with the losses connected with the mirrors and for this reason extreme cleanliness must be observed for reproducible maximum power operation. Also, slight variations in the quality of the mirrors can markedly affect the operation of the laser, making selection of the optimum final mirror for any laser cavity difficult.

During the period of the tests on mirror transparencies the overall qualities of the mirrors were still substantially below that which was desired. The maximum power output obtained with inferior quality mirrors for the long laser was 25 mw operating multimode, and about 10 mw operating single mode. Subsequent tests on 50 cm long lasers resulted in maximum power outputs of about 15 mw multimode. To the knowledge of h nu systems, the highest power output for a 50 cm long conventional unfolded laser tube has been 40 mw obtained by D. Perry* of the Bell Telephone Labs. In this case the output from his 5 mm bore, d-c pumped tube was multimode. This high power output was obtained with a set of experimental mirrors developed at Bell Labs. For comparison purposes, "top quality" mirrors fabricated by other commercial firms were tested on the same laser which has put out 40 mw. The results showed a large spread in the maximum power output with a minimum of about 8 mw and the maximum about 28 mw, indicating a tremendous variation in the actual quality of supposedly excellent mirrors from commercial firms.

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6.0 TUBE FABRICATION AND PROCESSING

Tests made during the processing of several test laser tubes revealed that one of the most insidious sources of scattering loss from Brewster windows is generated during laser tube construction. Early tubes were constructed after the Brewster windows had been attached to the Brewster tube ends. Since the plasma tube is quartz, the operation of joining Brewster tubes to the plasma tube engenders temperatures in excess of 1200° C. Quartz decomposes during fusion and creates finely divided white particles or dust which inevitably condenses out on the coldest surfaces within the tube and contaminates Brewster windows. Tests were made to attempt to eliminate quartz decomposition by flowing an inert gas through the plasma tube during the sealing operation. This proved to be of no avail. It is apparent that ingredients of quartz dust are part of the quartz tube. Attempts were made to remove the dust by chemical means. Dilute hydrofluoric acid proved effective in cleaning the tube, but the acid also etched microscopic pits into the surfaces of the Brewster windows, resulting in increased scattering loss. After several attempts were made to overcome this problem, it was found that the difficulty could be circumvented if the complete plasma tube were initially constructed without windows. After the tube was thoroughly cleaned to remove quartz dust from all portions, the Brewster windows were cleaned with reagent grade solvents and were optically contacted to the appropriately configured Brewster pipes. The windows were then cemented in place to provide additional mechanical strength. After tube processing the windows formed vacuum-tight integral seals to the plasma tube.

If the Brewster window of a plasma tube causes distortion of an otherwise plane wavefront the defect will accentuate walk-off errors that will tend to decrease the cavity Q of the desired lowest order mode. Several techniques were investigated in attempts to minimize this as a source of power loss. These included cementing, soldering, fusion and optical contacting.

Brewster windows of median optical quality were attached to laser tubes with low vapor pressure epoxy cements, including Torr seal (Varian), Hysol and Omniseal. The first two cements formed excellent bonds, but decomposed badly during plasma tube processing. Omniseal withstood bake temperatures in the region of 300° C, but was very inconvenient to process as it does not acquire a set at room temperature. In all cases, it was found that the cements produced deposits on the inner of the Brewster window surfaces that were intolerable for high performance lasers. It was concluded that no known epoxy cement would make a satisfactory seal-out for the laser required for this contract.

A search of the literature revealed two techniques for attaching laser windows by fusion. Test tubes were constructed wherein large diameter windows were fused to end bells at the extremities of the plasma tube in accord with the techniques developed at the Bell Telephone Laboratories. It was found that the windows so attached exhibited considerable strain and were typically distorted to an irregular 5 - 7 wave surface though the initial windows were flat to 1/20th wave. The windows used were 2 - 4 mm thick, and approximately 5 cm in diameter. These windows were further distorted under vacuum loading conditions. It is possible that windows 10 - 20 mm thick could be fused without distortion if the seal were made at a feathered edge. This technique has been used with some success by the laser group at the National Research Council at Ottawa. An objection to use of a fusion technique for the 50 cm laser is that large thick windows greatly waste cavity space and may cause a problem with quartz dust. Effort on using this sealing technique was tabled pending the results of two other methods described below.

The necessity for preserving high optical quality in the Brewster windows led to attempts to use low vapor pressure solders that would wet quartz. Both indium and an indium eutectic solder were tried. Ultrasonic soldering techniques were used to wet the surfaces. This technique was not exhaustively explored as the competing technique outlined below proved effective.

The art of optical contacting was evaluated as a technique for producing a vacuum tight bond between two surfaces without introducing distortion. This technique, though extremely tedious and requiring two additional high quality optical surfaces on each plasma tube, proved to be extremely effective. There are several serious pitfalls in the technique which had to be circumvented to assure perfect seals. These included

a) very smooth, flat, chemically-clean surfaces,
b) complete freedom from dust in the assembly operation,
c) great care in the assembly to preclude scratching of the mating optical surfaces,
d) selection of the proper lens tissue to eliminate fine scratches and lint,
e) selection of a bonding agent that would hold the components together without separating them during temperature cycling and would not decompose during plasma tube processing.

The most frustrating problem turned out to be obtaining optical surfaces that were of sufficient quality to permit reliable contacting. It became quite apparent that most optical finishing sources are not able to supply components of interferometric grade. The optical quality of the surfaces from Halle were found to be satisfactory. Test surfaces from other sources proved to be inconsistent in their quality.

While optical contacting was found to produce excellent seals between ideal surfaces, the technique, to be useful, must also preclude surface distortion of the Brewster window. The use of thick windows precludes surface distortion at the expense of inactive plasma tube length. It was found that windows of approximately 3 mm thickness could be held to desired surface figures if the optical contacting area was made as large as possible consistent with adequate beam aperture. This, however, created another problem. The large area precision optical surface represented by a thick-walled Brewster pipe could not be maintained when the pipes were fused to the plasma tube. This problem was finally solved by attaching a thin-walled section to the Brewster pipe prior to grinding. This assembly was then processed to produce the optical surface for contacting. The completed ends were fused to the plasma tube and, as mentioned above, the windows were added in the last stage in assembly of the plasma tube.

It is believed that the techniques needed for application of precision optical windows to the high power laser have been developed to a state of perfection that is now limited by the optical homogeneity, figure, and surface smoothness of the

Brewster window material. Even with these techniques significant scattering losses at Brewster windows are visible inside a high power optical cavity.

The first plasma tubes which were processed for investigation of excitation characteristics were evacuated with a silicon oil vapor diffusion pump. Condensibles were removed from the system under test with conventional liquid nitrogen traps. It soon became apparent that tubes which were processed on this vacuum system would not yield the necessary high power density performance characteristics required for the 50 cm laser.

The low performance index was initially attributed to degassing of the quartz plasma tubes with the subsequent release of carbon dioxide, water vapor, nitrogen, etc. that "poisoned" the plasma as well as to the loss of helium. It was, however, noticed that the power output of continuously pumped plasma tubes deteriorated with time, even though the discharge tubes were flame baked and refilled with new charges of laser gasses. Certainly part of this effect in the first tubes was due to the continuous deposition of the decomposition products of epoxy resins on the Brewsters-angle windows. It was found, however, when tubes with fused windows were used, that progressive deterioration in performance of continuously pumped lasers did not improve with elimination of the epoxy resins. It was concluded that the loss of power was due to silicon oil backstreaming from the vapor pump.

At first, attempts were made to improve performance through more careful and prolonged plasma tube bake-out with heating tapes, and the use of more and larger liquid nitrogen traps. While the above techniques produced base pressures an order of magnitude lower [10^{-7} Torr], indicating that the tubes were considerably cleaner internally, they did nothing to retard the progressive deterioration. It became evident that the attainment of the desired high-power performance could not be obtained with tubes processed on a vapor pump system.

h nu systems then designed, developed and constructed at Company expense, a complete high temperature bake-out facility which enabled tube processing at temperatures up to 500°C. This processing station was also provided with two Vac-Ion pumps, an absolute pressure measuring facility, and a gas filling station constructed in accord with the most modern ultra-high vacuum processing techniques.

The first tubes that were processed on this new system were baked on a carefully designed processing schedule so as to achieve the maximum performance consistent with the capability of this high vacuum processing station. The results were spectacular. The base pressure of tubes prior to gas filling improved by a factor of 10^5. Tubes which were processed on this system and filled with the proper gas mixtures exhibited considerably improved gain characteristics and did not show the usual deterioration of tube life with time. To date, none of the tubes processed on this new high vacuum filling station have yet shown appreciable deterioration in life, even though they were constructed without large gas ballasts.

Considerable improvement in the precision and control of the gas filling was obtained in the system through the installation of a precision capacitive manometer that permitted accurate measurements of absolute gas pressure (independent of mass), in that pressure range wherein oil manometers were formerly used. As this gauge (which was also purchased and installed by h nu systems as a capital equipment item) is capable of electronic differential pressure measurements, the accuracy with which differential pressure measurements could be made was also improved. h nu systems also provided a precision aneroid-type pressure gauge for the mixing chamber of the filling station to cover the pressure range from 1 - 400 mm with 3% accuracy.

7.0 SUMMARY

For the case of a He-Ne laser the attainment of maximum TEM_{00} power output at 6328 Å requires the following conditions:

a] Diffraction losses be introduced into the laser cavity to obtain the required discrimination against higher order modes. Techniques based on the diffraction-loss laws must be used which will give minimum loss for the desired TEM_{00} mode and maximum loss for all higher order modes.

b] All techniques for maximizing the gain of the laser transition must be utilized and improved upon so that the greatest efficiency in the desired laser transition can be obtained. This involves construction of a laser tube with extremely low loss windows that have flat and parallel surfaces, and that have low index of refraction dispersion so as not to cause distortion of the laser wave front. Generation of hyper-smooth laser mirrors of high surface figure are required, along with mirror coatings having extremely low scatter and absorption loss. It is necessary to design the laser to retard competing transitions using magnetic field effects. Selection of gas mixture and pressure for maximum gain is also important. Matching the electrical characteristics of the laser tube with an appropriately regulated power supply yields maximum laser efficiency and stability. A mechanical design that allows the largest possible length of active plasma between the cavity mirrors is paramount.

The laser system designed for this contract utilizes a very compact mechanical system which optimizes the ratio of active plasma length to overall length. The system has been designed to be compatible with laser tracking systems by the inclusion of precise laser beam steering controls in which the angular position can be controlled to 0.02 sec. of arc with minimum backlash.

The highest quality Brewster windows and mirrors obtainable were used. Although it was not possible to obtain the quality of optics desired or required, much advancement was made by commercial firms in the fabrication of these critical items during the course of the program. It is clear that commercially available mirror quality is not equal to that obtained at the Bell Telephone Laboratories.

Excitation studies and gas filling parameters for the laser tube were carefully studied before a decision was made on the optimum excitation requirements. D-c pumping was observed to give the highest power output at the proper laser gas pressure. The final exciter consists of a regulated 2500 v d-c, 50 ma power supply matched in voltage and current to the laser tube, and including a trigger circuit for easy starting of the laser. The output of the power supply is variable so that continuous control of the laser current and, therefore, the laser output power, is available over large ranges.

The optical configuration of the laser cavity was finalized in the hemispherical mode. Although this mode does not deliver the maximum laser power, it offers the best mode discrimination values for operation in a single transversal mode. By assembling the lasers in a confocal geometry which offers the advantage of high power operation, a maximum of 15 mw of 6328 Å laser power was achieved, but the laser would operate only multimode due to the low diffraction losses for this configuration. The hemispherical cavity was assembled with the use of two mirrors, one polished by Halle of Germany and coated by Thin Film Products, Inc., the other was supplied by the Perkin-Elmer Corporation. The maximum power obtainable in the hemispherical configuration was 2.5 mw in the lowest order transverse mode. It is felt that this power level could be substantially increased by the use of higher quality mirror optics of greater transparency. Although not all avenues have been exhausted in the search for techniques which will give 50 mw in 50 cm, it does not appear feasible at the present state of the art that the required power levels can be obtained until mirror quality can be improved.

8.0 AREAS OF FUTURE INVESTIGATION

The problems in obtaining specific powers of over 1 mw/cm for a 50-cm laser are at best very difficult for single mode operation. If multimode operation is acceptable, then the 50 mw level apparently can be achieved by increasing the bore of the tube to about 7 mm diameter [see Ref. 7] and obtaining better quality mirrors.

It is felt that the main area to be still attacked is the availability and test of top quality laser mirrors (both surfaces and coatings). The state of the art in producing the required commercial low loss dielectric films has not proceeded to the point where a critical design can be made of a very high power density laser system without considerable trial and error. Evaluation techniques are still lacking for the determination of substrate quality <u>before</u> coatings are applied. Also, Brewster window quality selection techniques need to be improved.

Another area which was not studied in detail during this program is that involving the folded tube techniques used for larger laser systems. This technique for increasing the effective length of the laser tube obviously could be used if the very difficult problems of obtaining low loss beam bending components can be solved and thermally stable alignment systems were evolved.

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